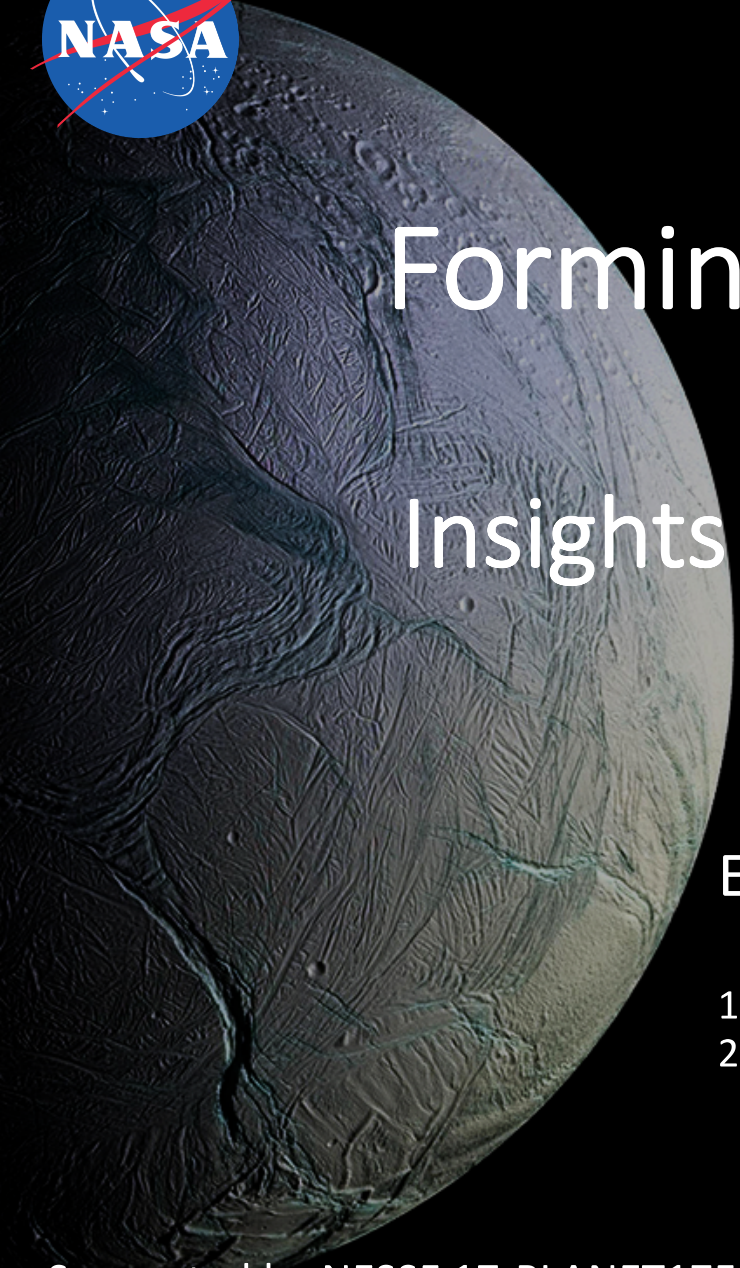

Forming Ridge-and-Trough Systems on Icy Satellites: Insights from Physical Analogue Modeling

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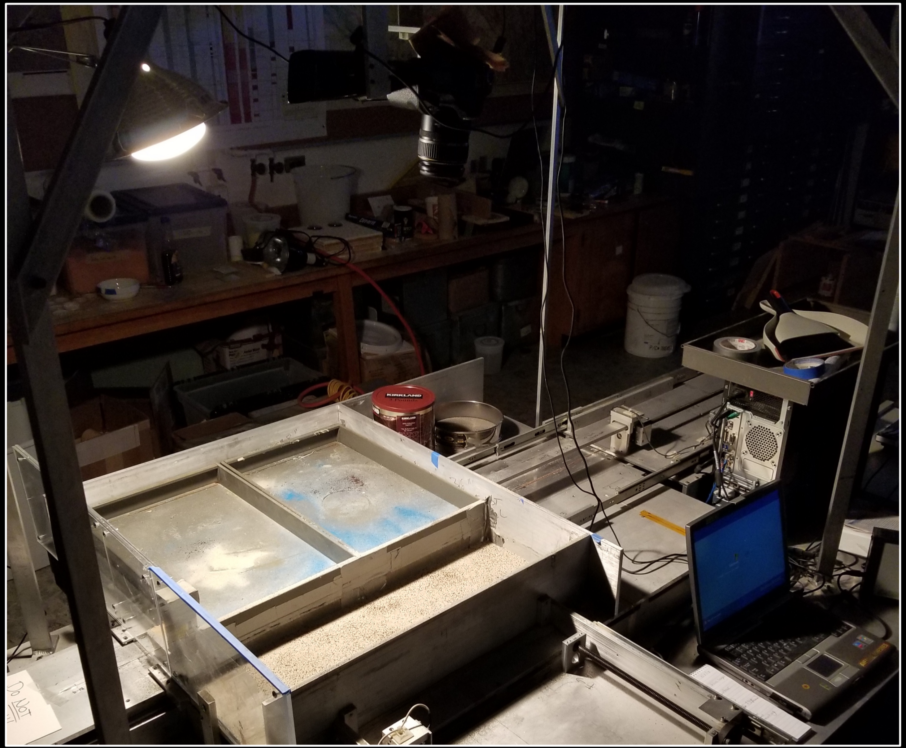
Overview

- Observations and Motivation
- Analogue Set-up
- Experiment Results
  - No Ductile Layer
  - Brittle layer thickness – compression
  - Ductile layer thickness
  - Extension
  - Scaling to ice shells
- Summary and Future Work



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    - No Ductile Layer
    - Brittle layer thickness – compression
    - Ductile layer thickness
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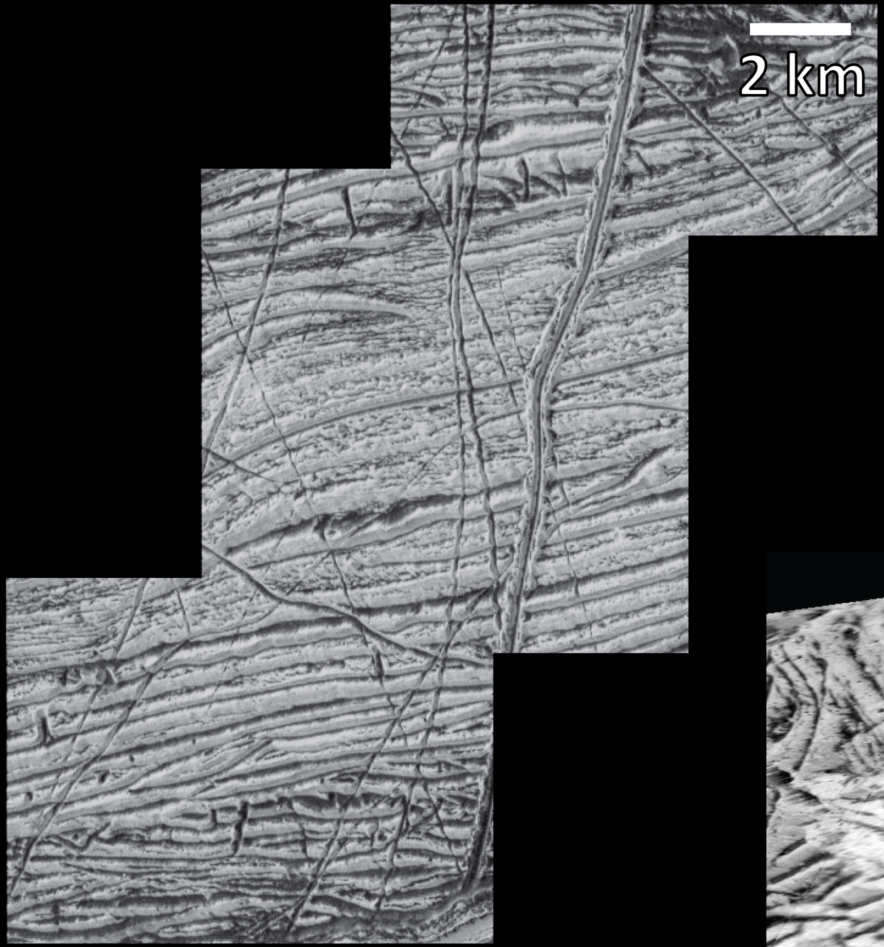
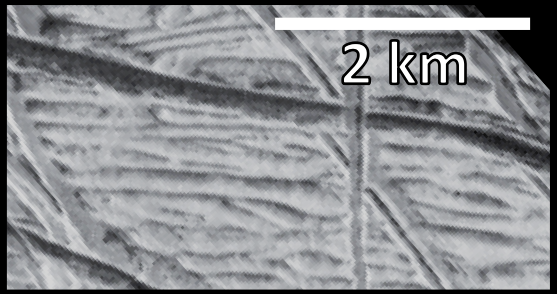
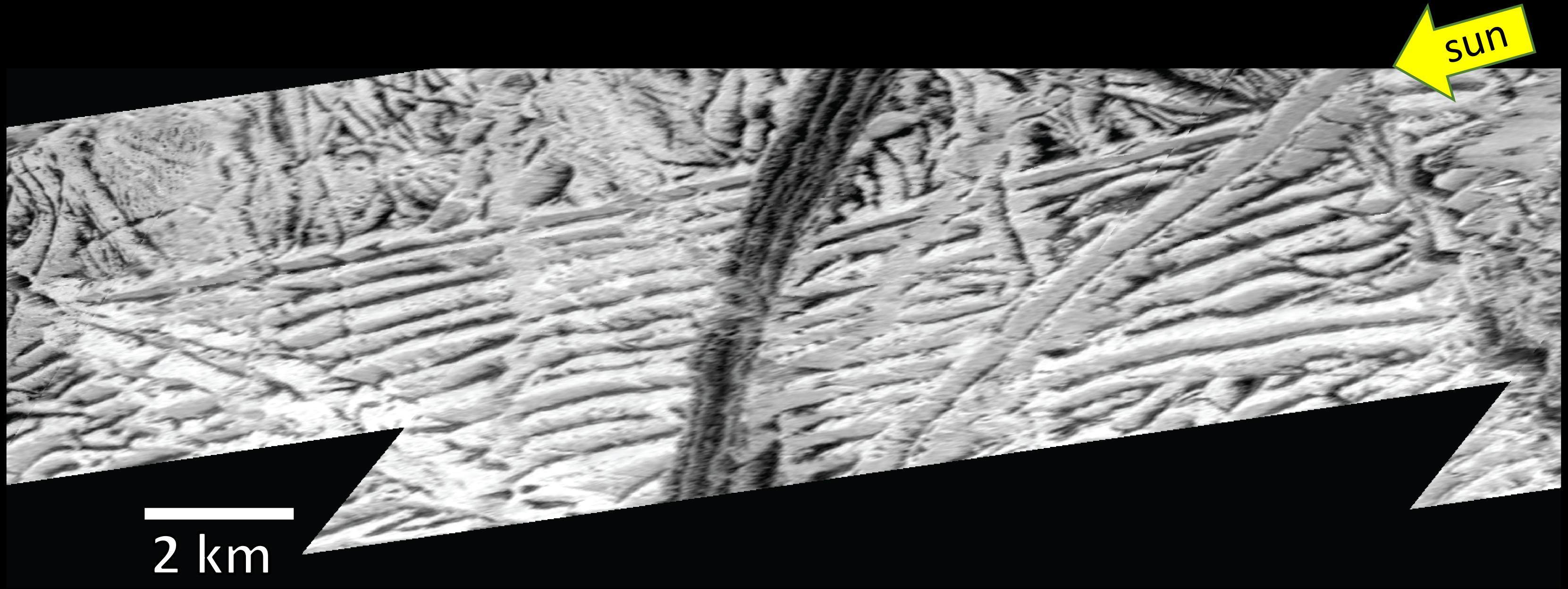
    - Scaling to ice shells
- Summary and Future Work

The ductile subsurface ice and brittle layer thickness are key to the formation of ridge-and-trough systems on icy satellites.

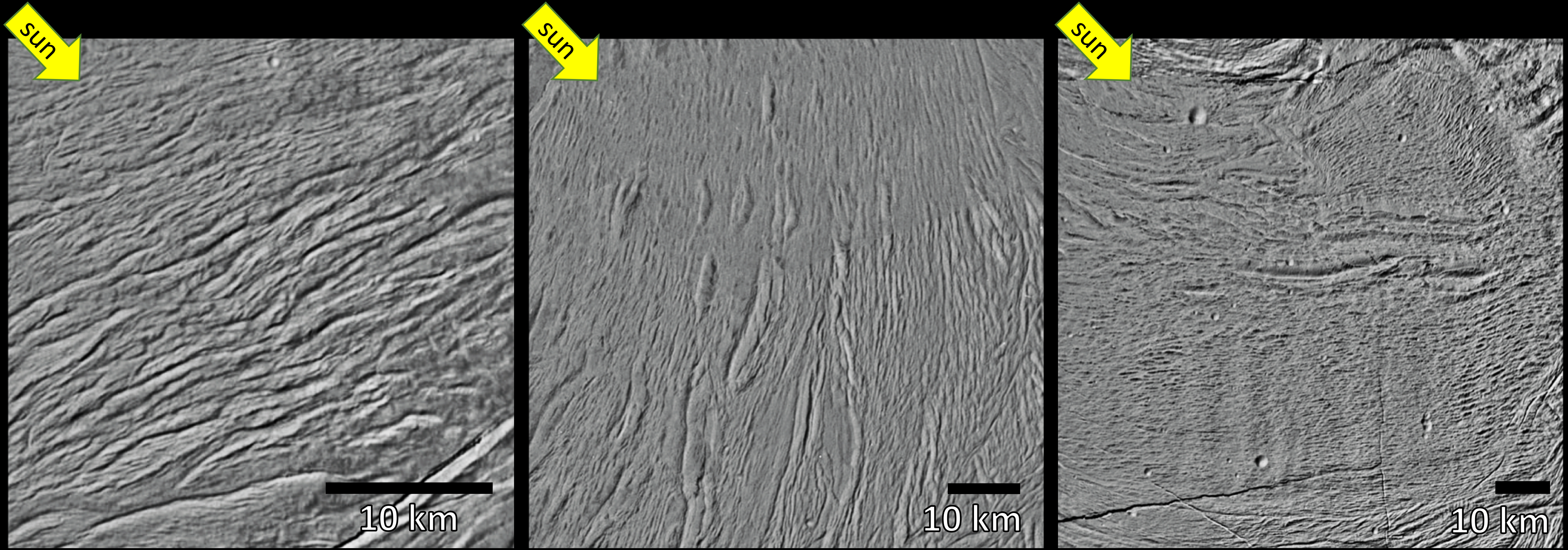
Ridges on Europa and Enceladus



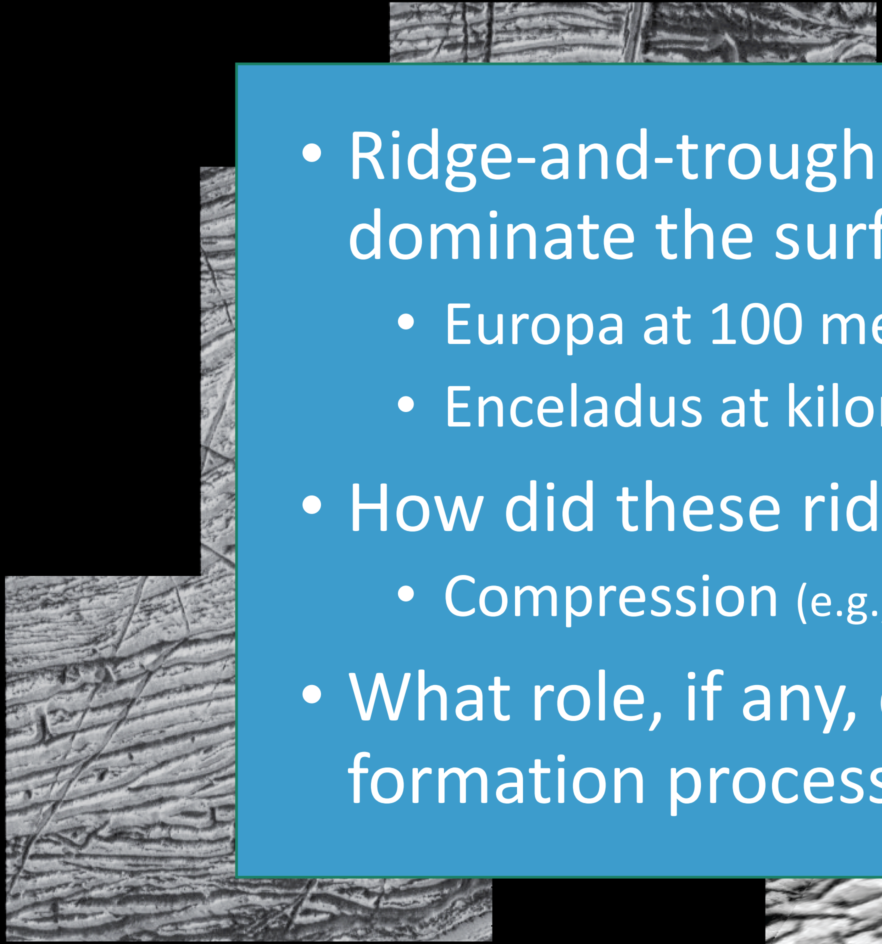


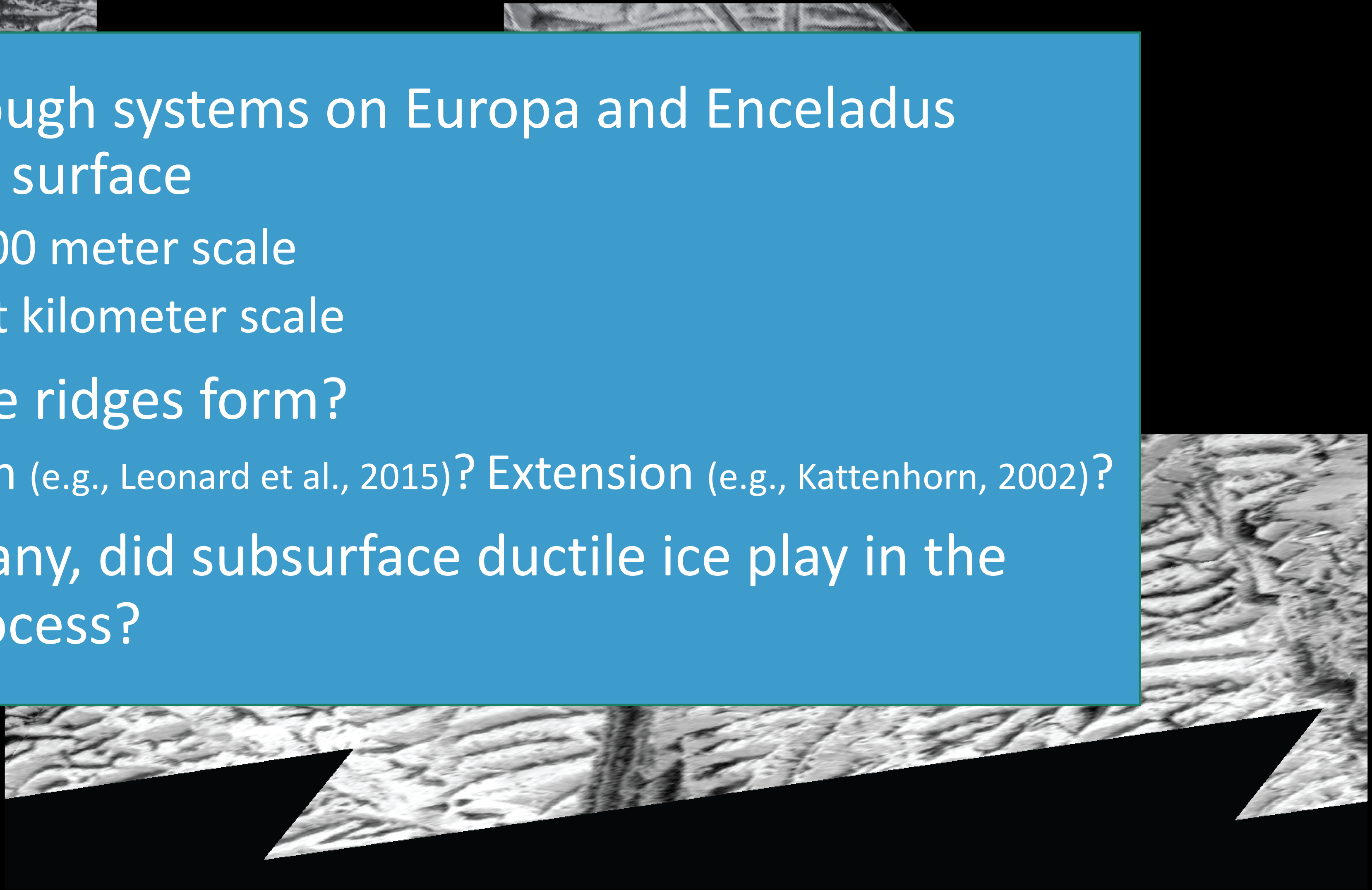


Ridges on Europa and Enceladus



Ridges on Europa and Enceladus





- Ridge-and-trough systems on Europa and Enceladus dominate the surface
  - Europa at 100 meter scale
  - Enceladus at kilometer scale
- How did these ridges form?
  - Compression (e.g., Leonard et al., 2015)? Extension (e.g., Kattenhorn, 2002)?
- What role, if any, did subsurface ductile ice play in the formation process?

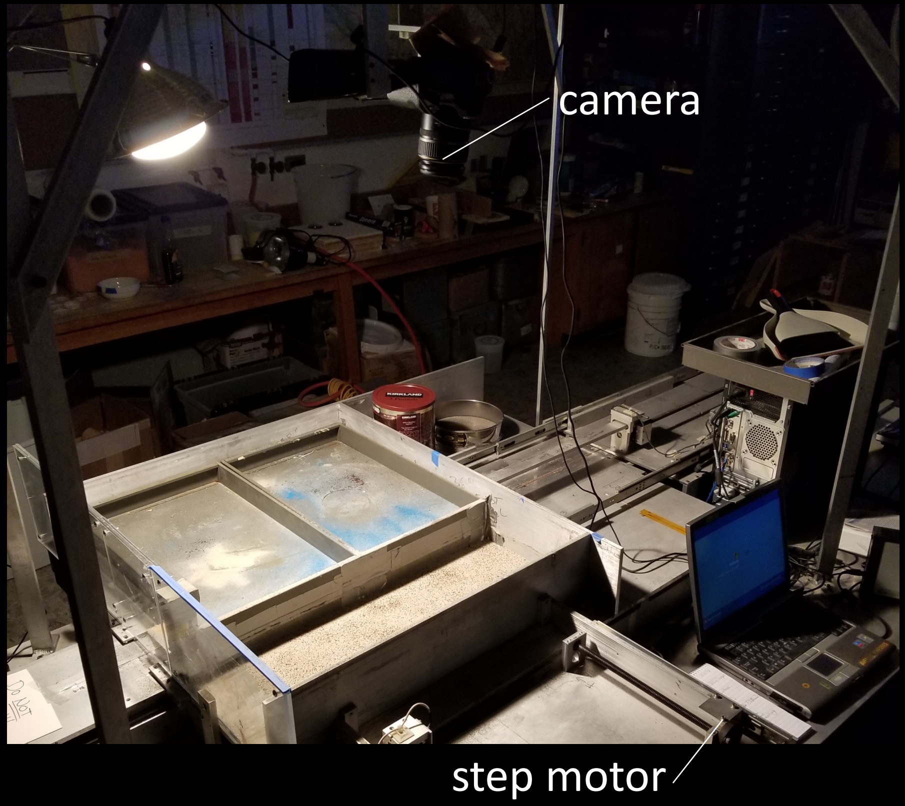
Analogue Experiments

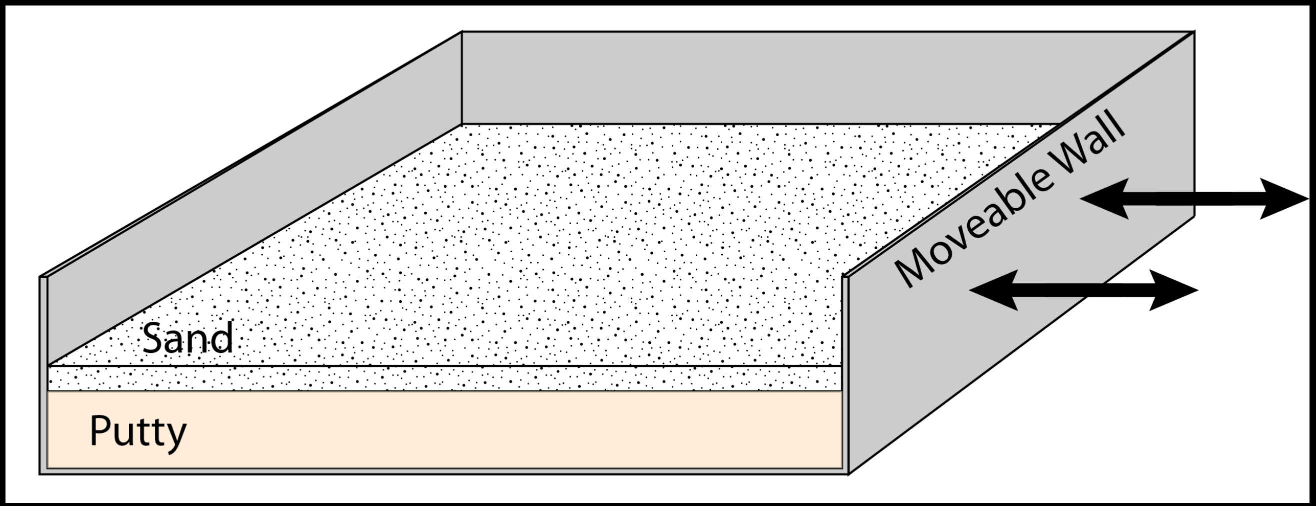
- Brittle layer = sand (~200 um)
- Scaling:
  - 1 cm model is 2 km on Europa
  - 1 cm model is 20 km on Enceladus

$$\boxed{\frac{h_{ice}}{h_{mod}} = \frac{\rho_{mod}}{\rho_{ice}} \cdot \frac{g_{mod}}{g_{ice}} \cdot \frac{C_{ice}}{C_{mod}}}$$

e.g., Cruz et al. (2007); Hubbert (1937)

- Coffee grounds sprinkled on the surface (passive markers)



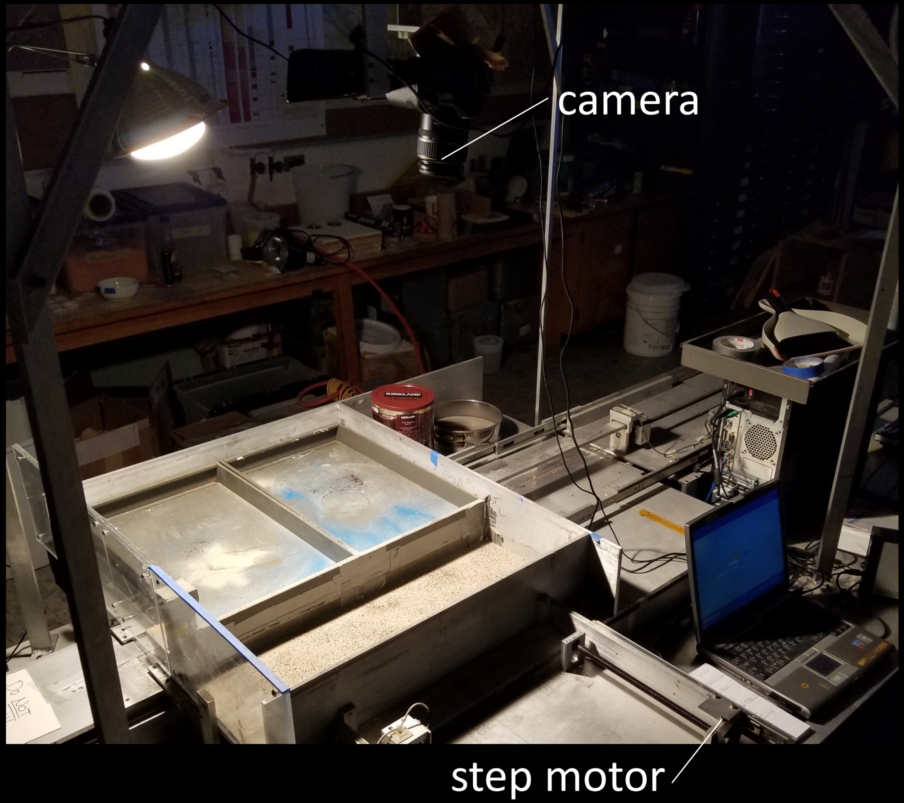


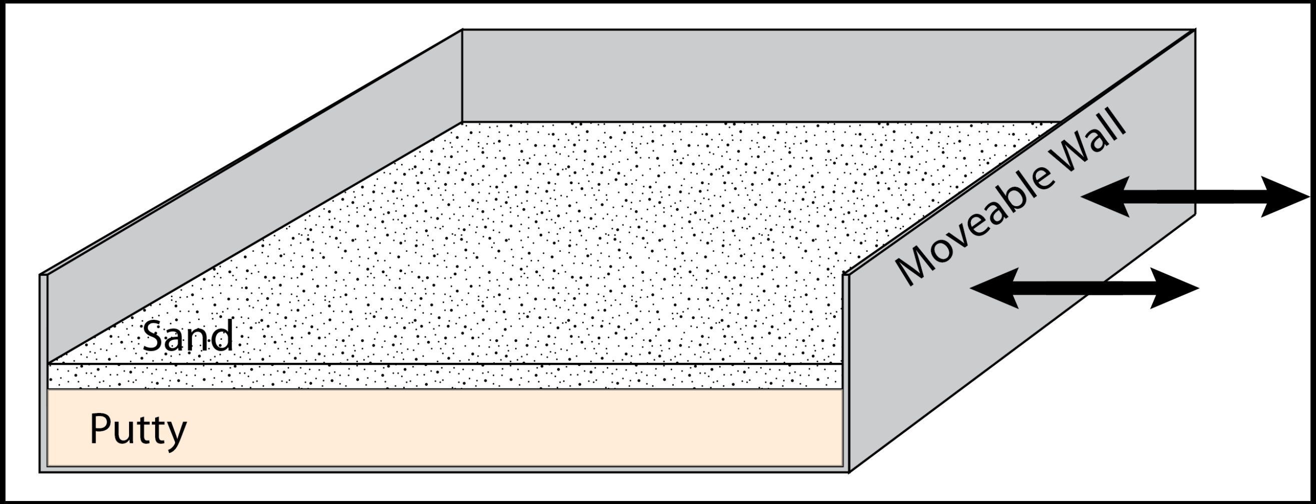
Analogue Experiments

- Ductile layer = putty (10^4 Pa s)
- Scaling:
  - 24 hours model is ~10^6 years on Europa or Enceladus
  - 10^{-5} s^{-1} model is 10^{-13} s^{-1} on Europa or Enceladus

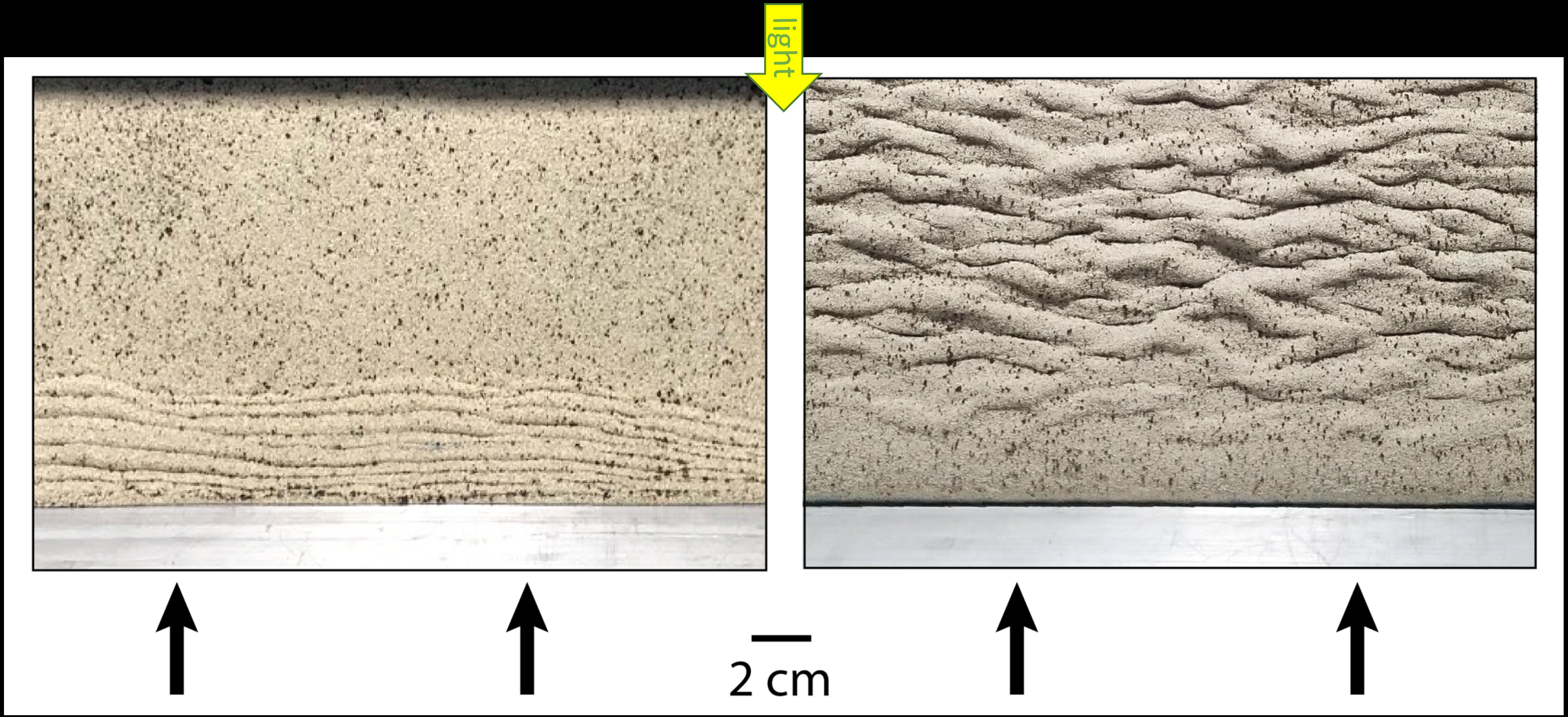
$$\boxed{\frac{t_{ice}}{t_{mod}} = \frac{\mu_{ice}}{\mu_{mod}} \cdot \frac{C_{mod}}{C_{ice}}}$$

e.g., Davy and Cobbold (1988)





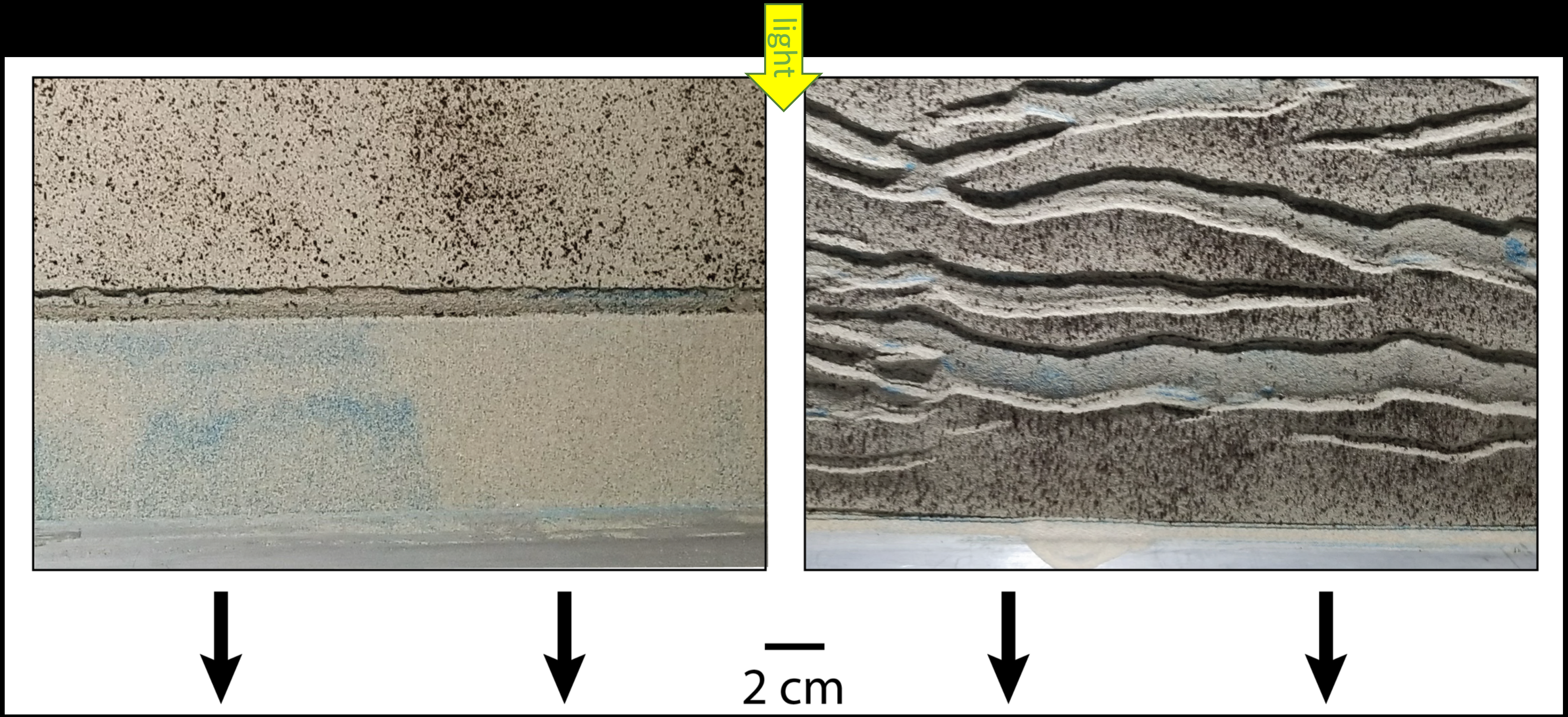
Results – Brittle vs. Brittle+Ductile Tectonics



Sand thickness ~0.25 cm

Sand thickness ~0.25 cm
Putty thickness ~2 cm

Results – Brittle vs. Brittle+Ductile Tectonics

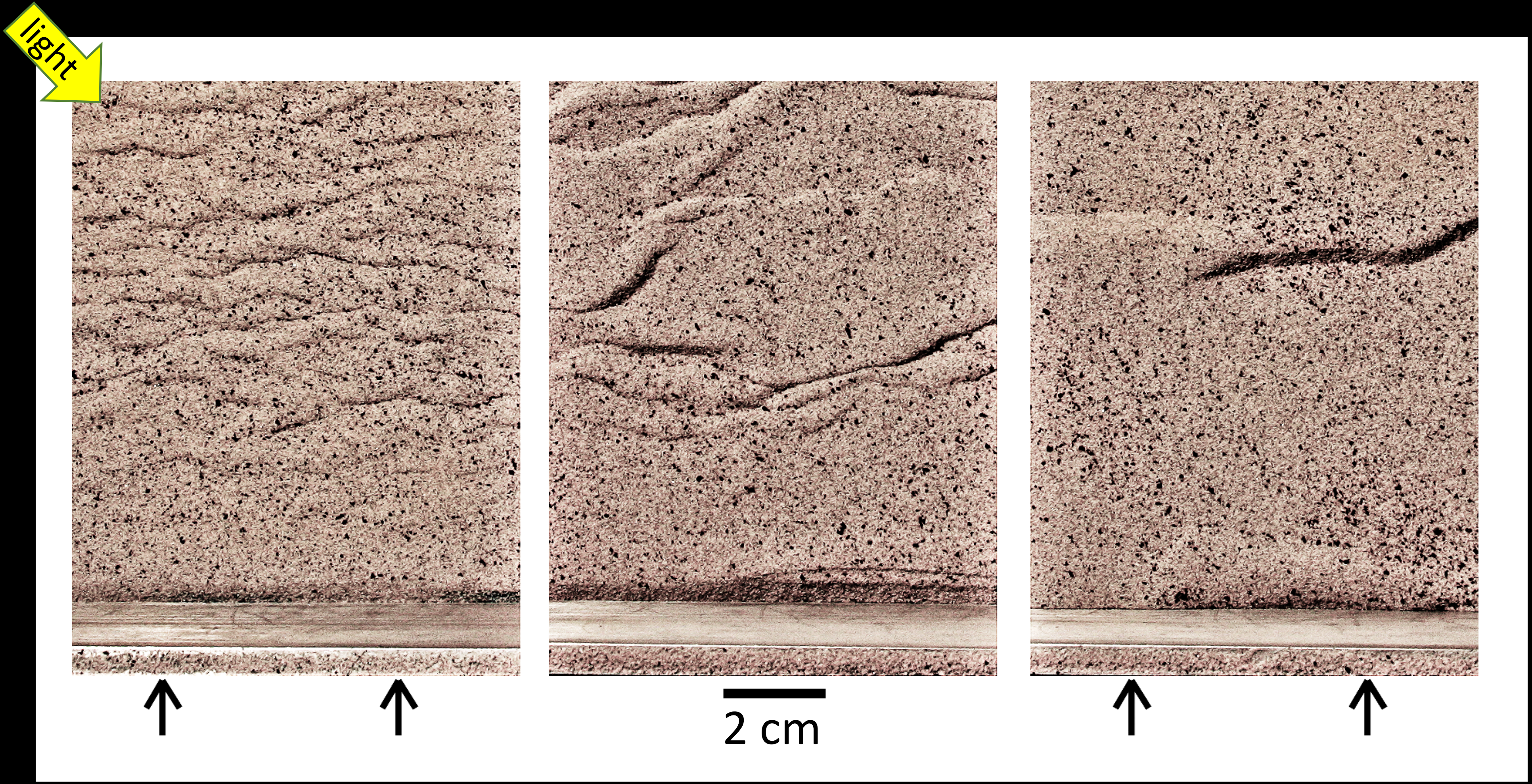


Sand thickness ~1.0 cm

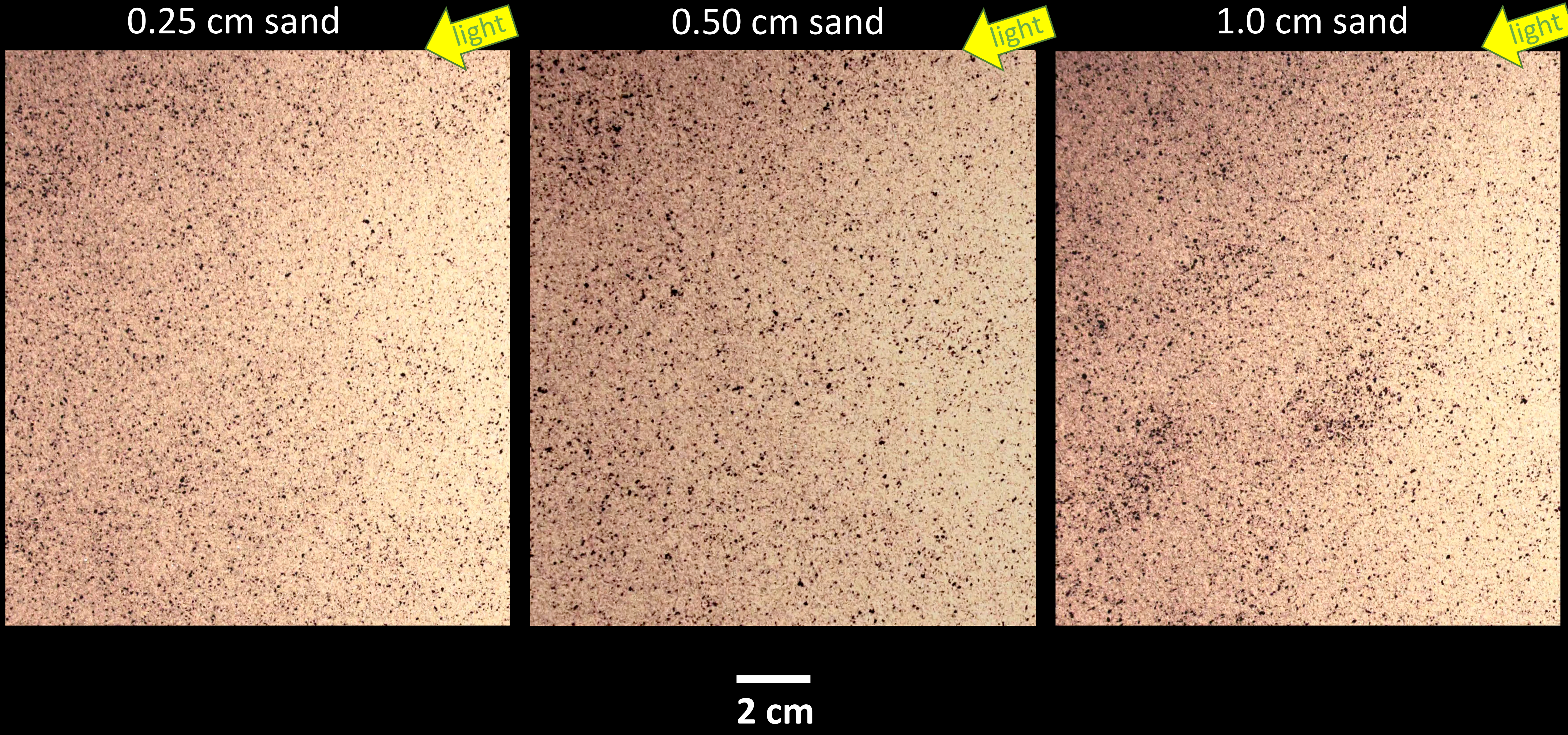
Sand thickness ~1.0 cm
Putty thickness ~2 cm

Results – Compression with Varying Brittle Layer Thickness

- Brittle layer thickness varied
- Putty thickness all ~ 2 cm
- Run for 24 hours, ~ 33% strain



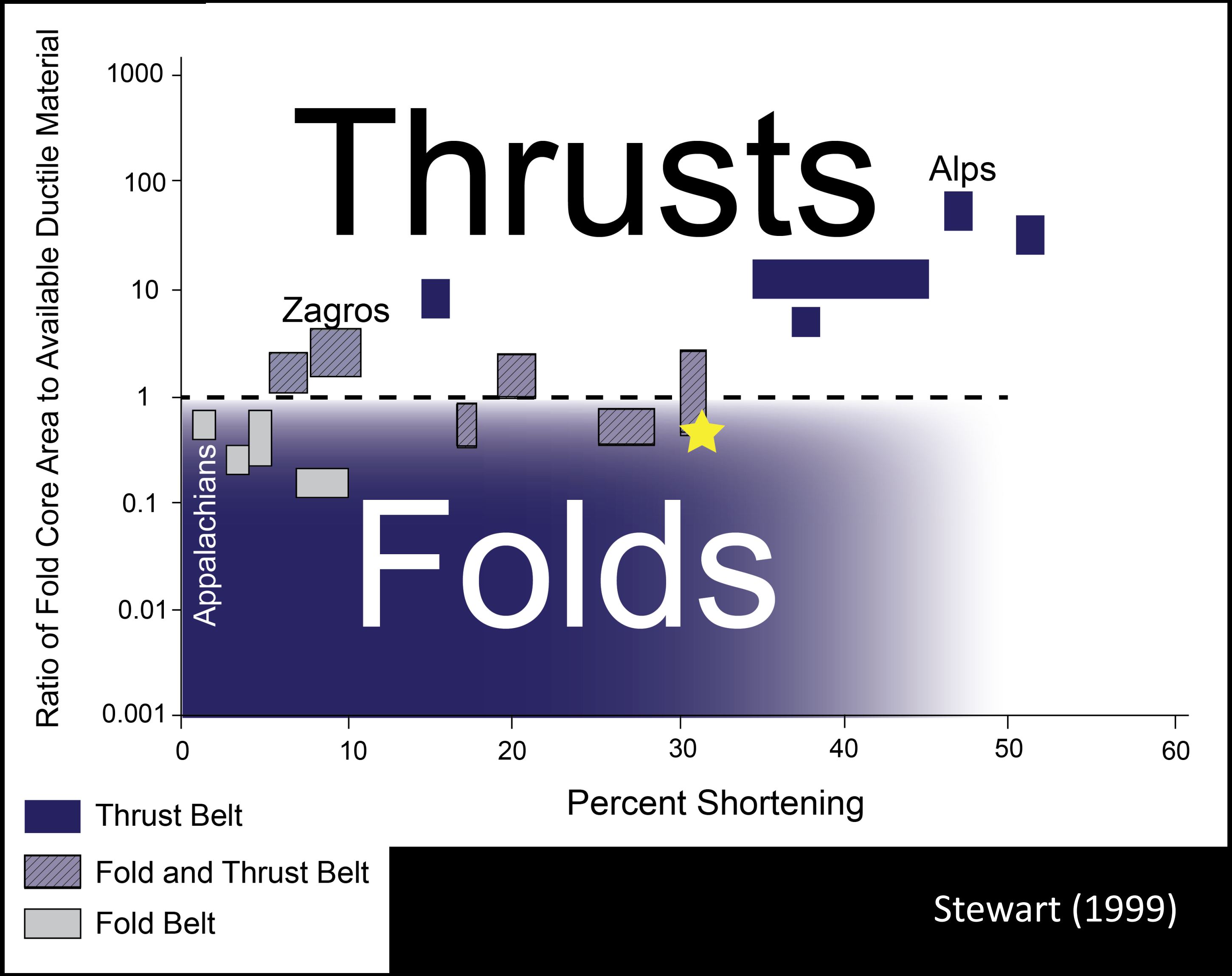
Sand thickness: ~ 0.25 cm ~ 0.50 cm ~ 1.0 cm


0.25 cm sand
light
0.50 cm sand
light
1.0 cm sand
light
2 cm

Results – Ductile Layer Thickness (Compression)

- Regime diagram from Stewart (1999)
  - Our compression experiments sit near the border of the transition from thrusts to folds

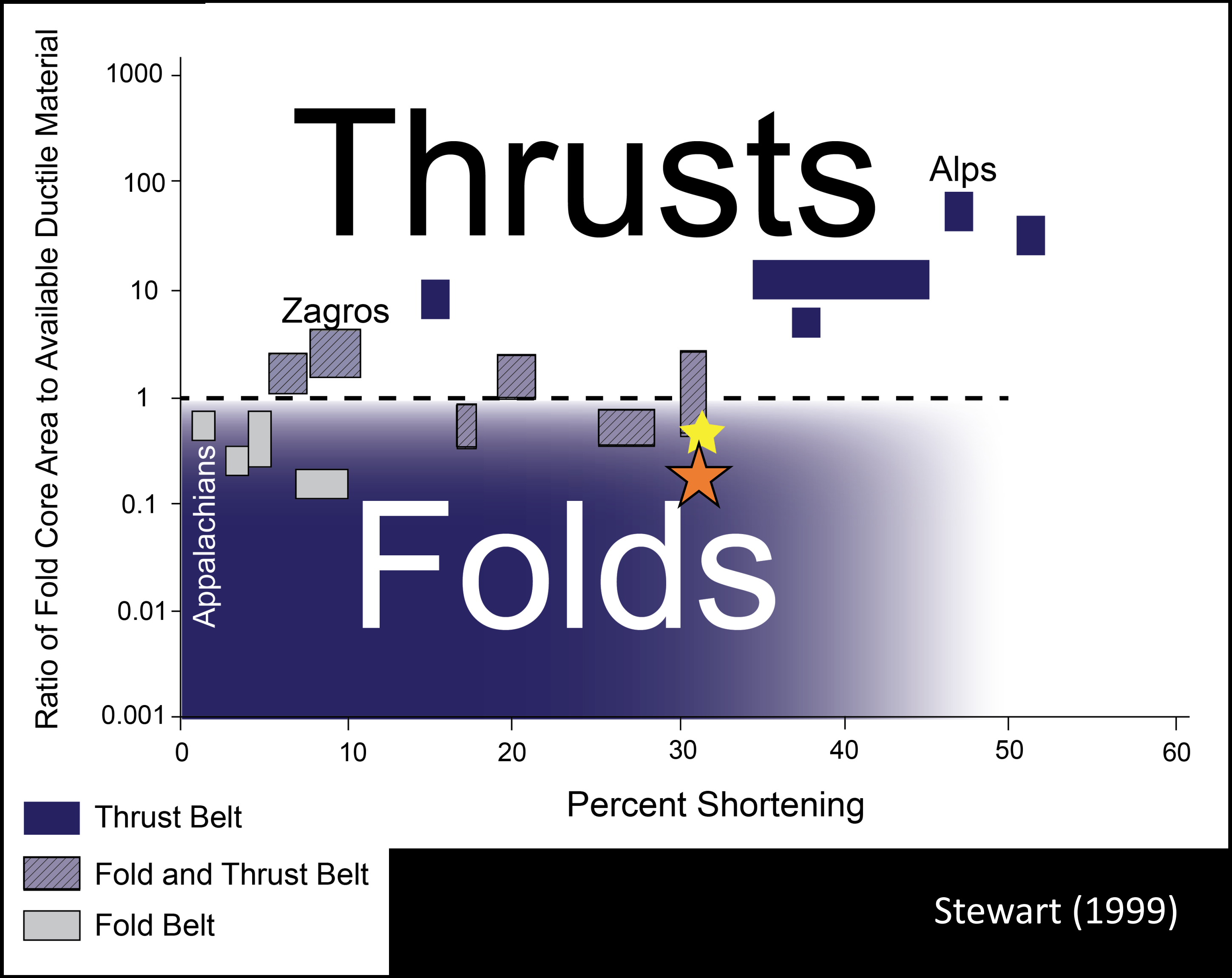
- The thickness of the ductile layer may be effecting the surface structures



Stewart (1999)

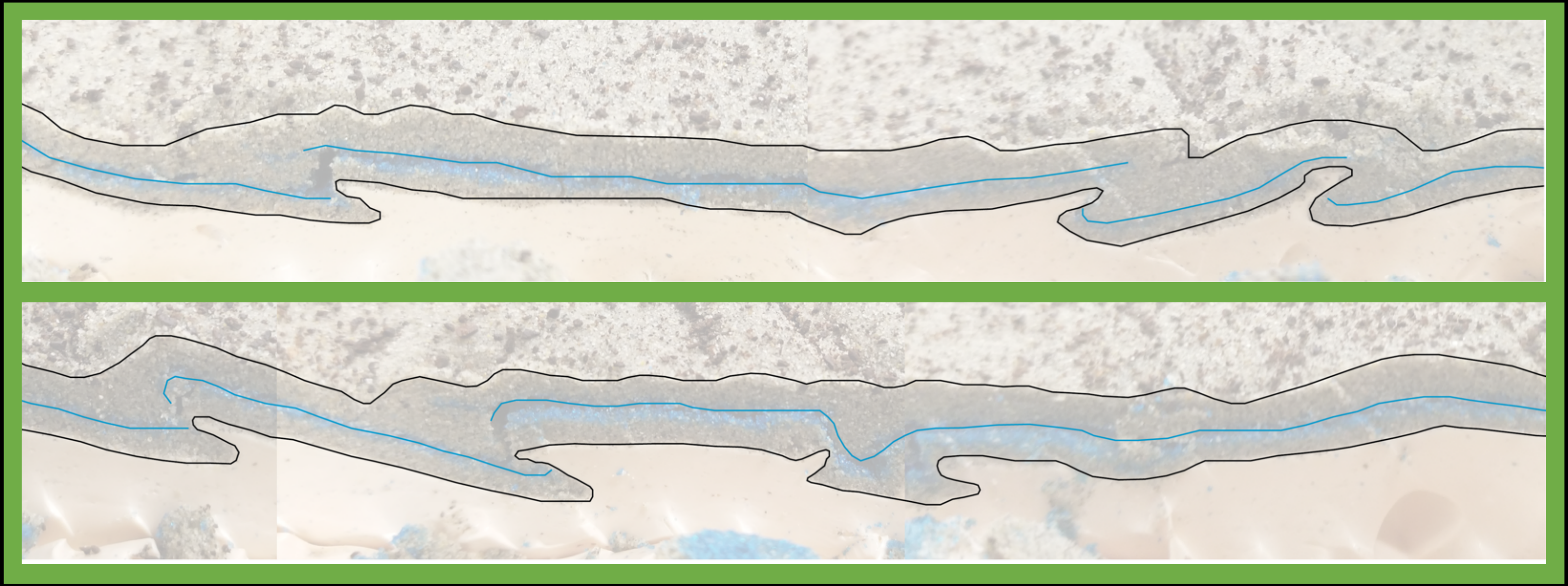
Results – Ductile Layer Thickness (Compression)

- Regime diagram from Stewart (1999)
  - Our compression experiments sit near the border of the transition from thrusts to folds
- The thickness of the ductile layer may be effecting the surface structures
  - Test it!



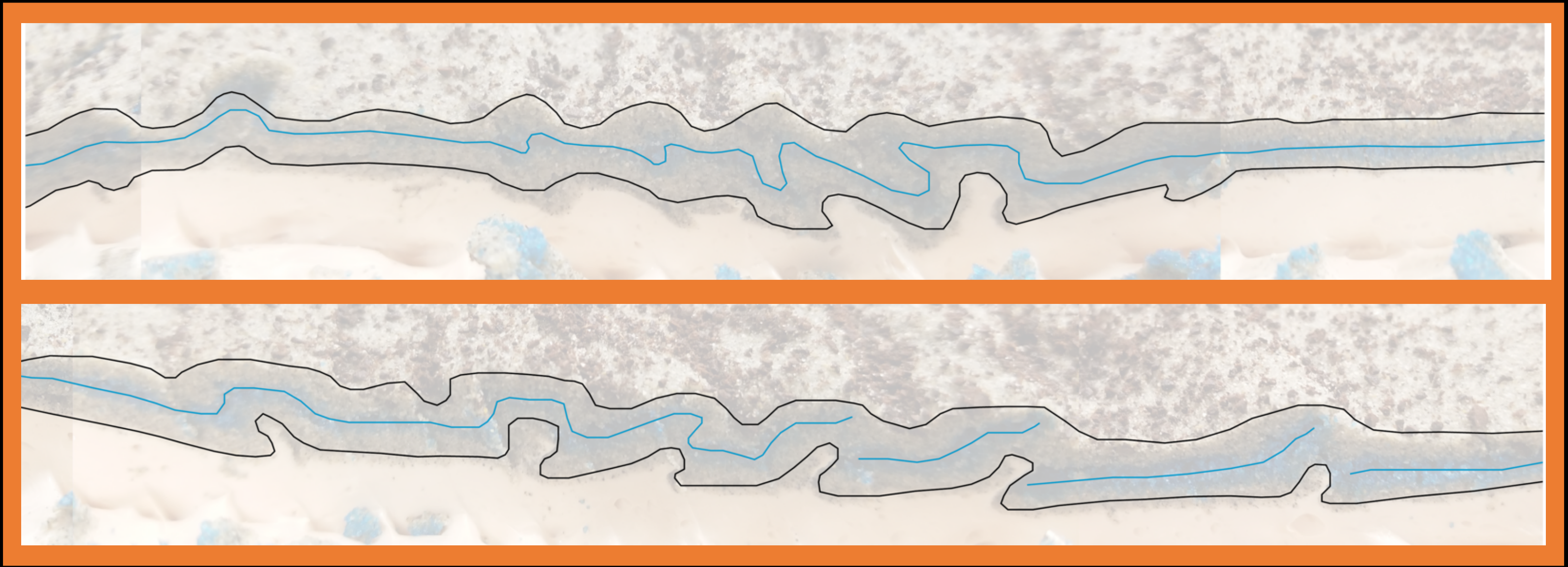
Stewart (1999)

Results – Ductile Layer Thickness (Compression)



- Putty thickness ~ 2 cm
  - Sand thickness ~0.5 cm
- Thrusts (1 - 2 cm wavelength) dominate

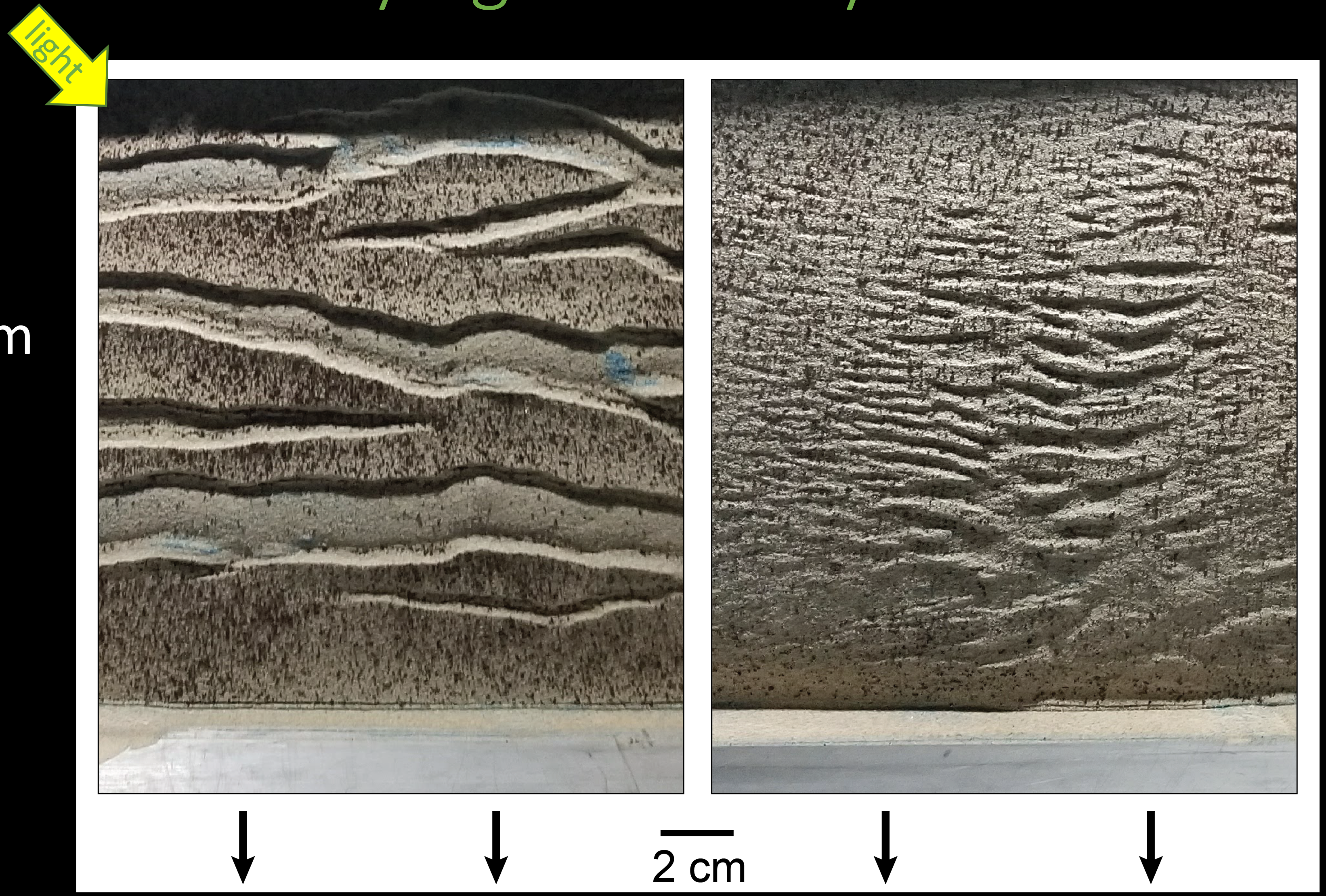
- Putty thickness ~ 4 cm
  - Sand thickness ~0.5 cm
- Folds (0.5 – 1 cm wavelength) dominate



Results – Extension with Varying Brittle Layer Thickness

- Brittle layer thickness varied
- Putty thickness all ~ 2 cm
- Run for 24 hours, ~ 33% strain

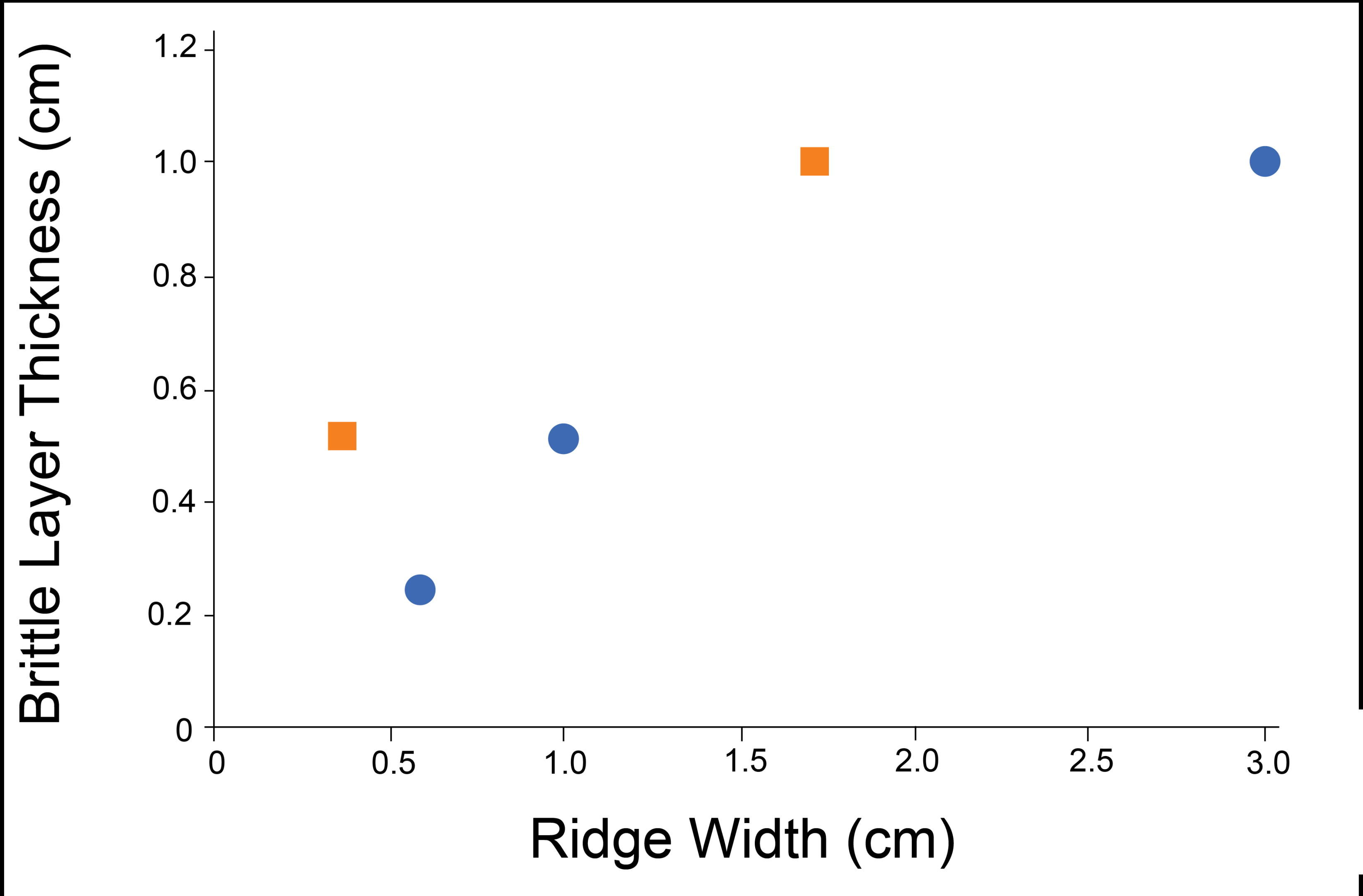
- Tilt-blocks only occur when extension rate is near or at maximum



Sand thickness ~ 1.0 cm

Sand thickness ~ 0.5 cm

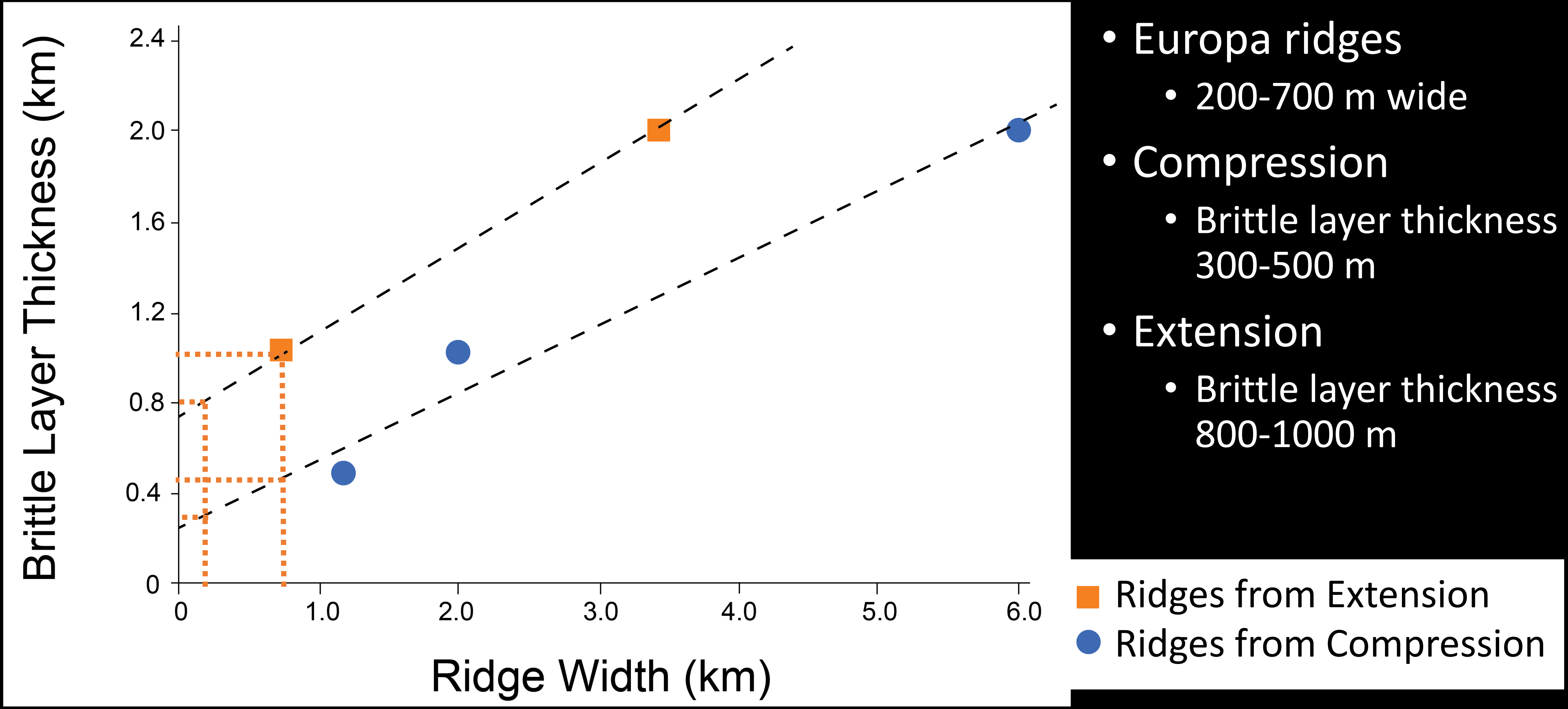
Results – Implications for Icy Satellites



- Ridge width produced by each extension or compression experiment

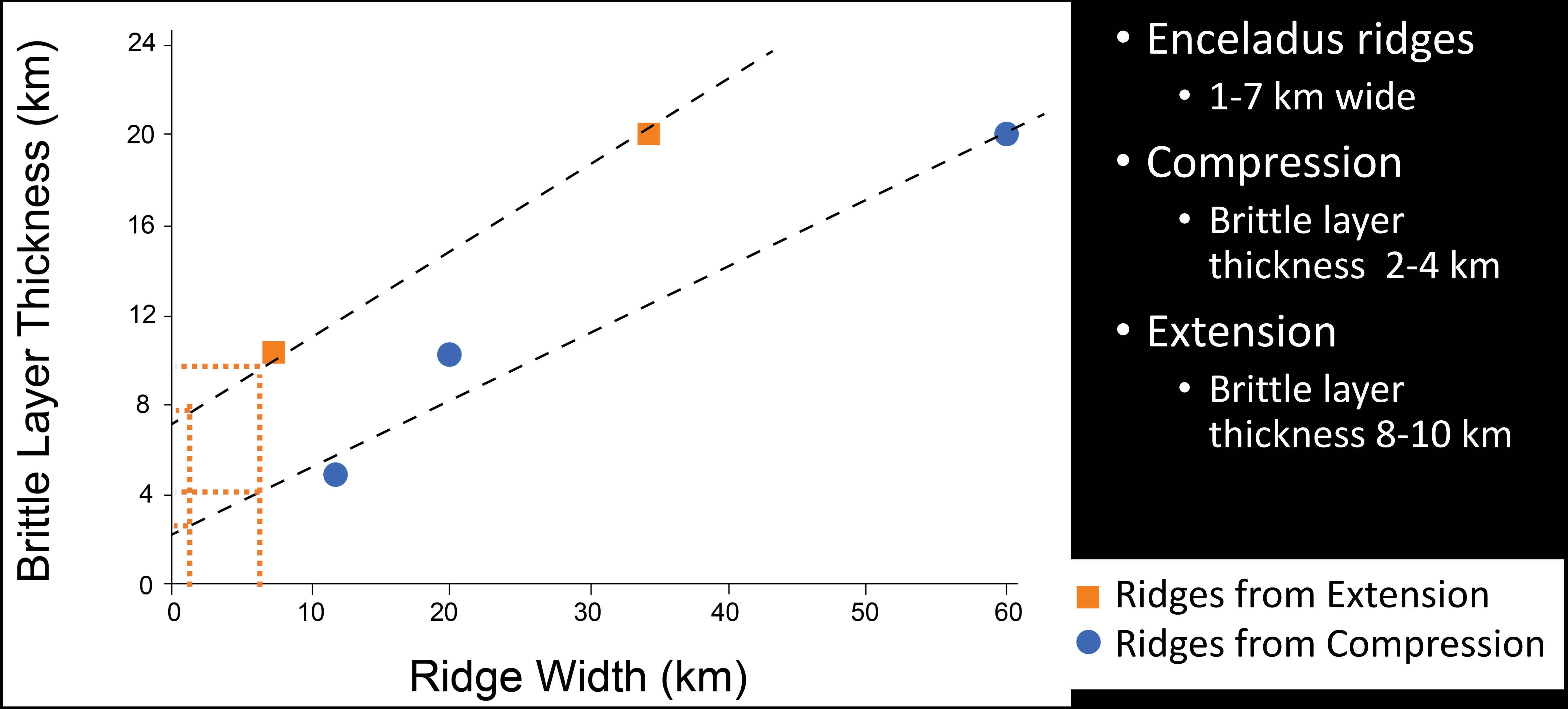
■ Ridges from Extension
● Ridges from Compression

Results – Implications for Europa



- Europa ridges
  - 200-700 m wide
- Compression
  - Brittle layer thickness 300-500 m
- Extension
  - Brittle layer thickness 800-1000 m

Results – Implications for Enceladus



- Enceladus ridges
  - 1-7 km wide
- Compression
  - Brittle layer thickness 2-4 km
- Extension
  - Brittle layer thickness 8-10 km

Highlights of Analogue Experiments

- The ductile ice and brittle layer thickness are key to the formation and morphology of ridge-and-trough systems
  - Implications for the evolution of the ice shell
- Total thickness of the ice shell or ductile subsurface ice could determine dominant process (e.g. thrusting vs folding)
- Europa ridge-and-trough terrain implies brittle ice thickness of ~0.3 to 1 km; Enceladus, ~2 to 10 km
- Further experiments and morphological analysis can constrain this further

2 km

2 cm